AN OPERATIONS MANUAL FOR ACHIEVING NITRIFICATION IN AN ACTIVATED SLUDGE PLANT

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of the
Environment

Ontario

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AN OPERATIONS MANUAL FOR ACHIEVING NITRIFICATION IN AN ACTIVATED SLUDGE PLANT

Wastewater Treatment Section
Pollution Control Branch
Ontario Ministry of the Environment

May, 1980

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1. *INTRODUCTION*

Currently, increased emphasis is being placed upon the attainment of nitrification (oxidation of ammonia) in activated sludge (A/S) plants in Ontario. In the past, plants in Southwestern Ontario have been affected due to recommendations from the Thames River Basin Study (1). Other areas in the province are now requesting nitrification of wastewater prior to discharge to a receiving water; each requirement being site-specific.

The objectives of the nitrification requirements are to reduce ammonia and possibly organic nitrogen in wastewater treatment plant effluents. These nitrogen forms exert a Nitrogenous Oxygen Demand (NOD) upon a receiving water which is approximately 4 times that of Biological Oxygen Demand (BOD) of a typical secondary effluent. NOD then represents the major portion of the Total Oxygen Demand (TOD). Ammonia is toxic to aquatic life in the un-ionized form (NH_3*) and it affects disinfection as efficient bacterial kill by chlorine (as HOCl) is hampered. Organic nitrogen is less of a problem, but can be coverted biologically to ammonia in the A/S system and the receiving stream thereby causing an oxygen demand.*

To many operations staff and their supervisors, this new requirement will mean added responsibility to recent demands of reduced allowable effluent BOD and phosphorus discharges to the Great Lakes Basin. Expansion and/or upgrading of a facility may be required at some sites to achieve nitrification. However, routine sampling programs by this Ministry have shown that many conventional A/S plants do, to varying extents, nitrify during the warmest six months of the year (2). Furthermore, many extended aeration systems show high nitrification efficiencies year round.

From this, it can be concluded that many A/S plants have inherent capabilities for achieving nitrification. The question then is whether refinement of facility operation would in some instances negate the need for expansion for nitrification. Nitrification can be enhanced by applying some simple theoretical principles to the routine operation of an activated sludge system.

The objective of this manual is to present the various aspects of nitrification and relate them to daily plant operation.

2. REVIEW OF ACTIVATED SLUDGE PRINCIPLES

Biological oxidation of both organic and inorganic compounds occurs naturally in soil and in surface waters by bacterial reduction and/or conversion of carbon and nitrogen compounds. The function of the A/S process is to duplicate these reactions under more controlled aerobic (with oxygen) environment; this being in the aeration basin .

To understand what possibilities are available in the activated sludge process, a knowledge of nature's carbon and nitrogen cycles is needed.

2.1 Carbon Cycle and the A/S System

As shown in Figure 1, there are several pathways by which carbonaceous materials (carbon compounds) can be converted to various forms by biological action. For the most part, the A/S system is concerned with conversion of organic carbon to carbon dioxide and water as shown in expression 1.

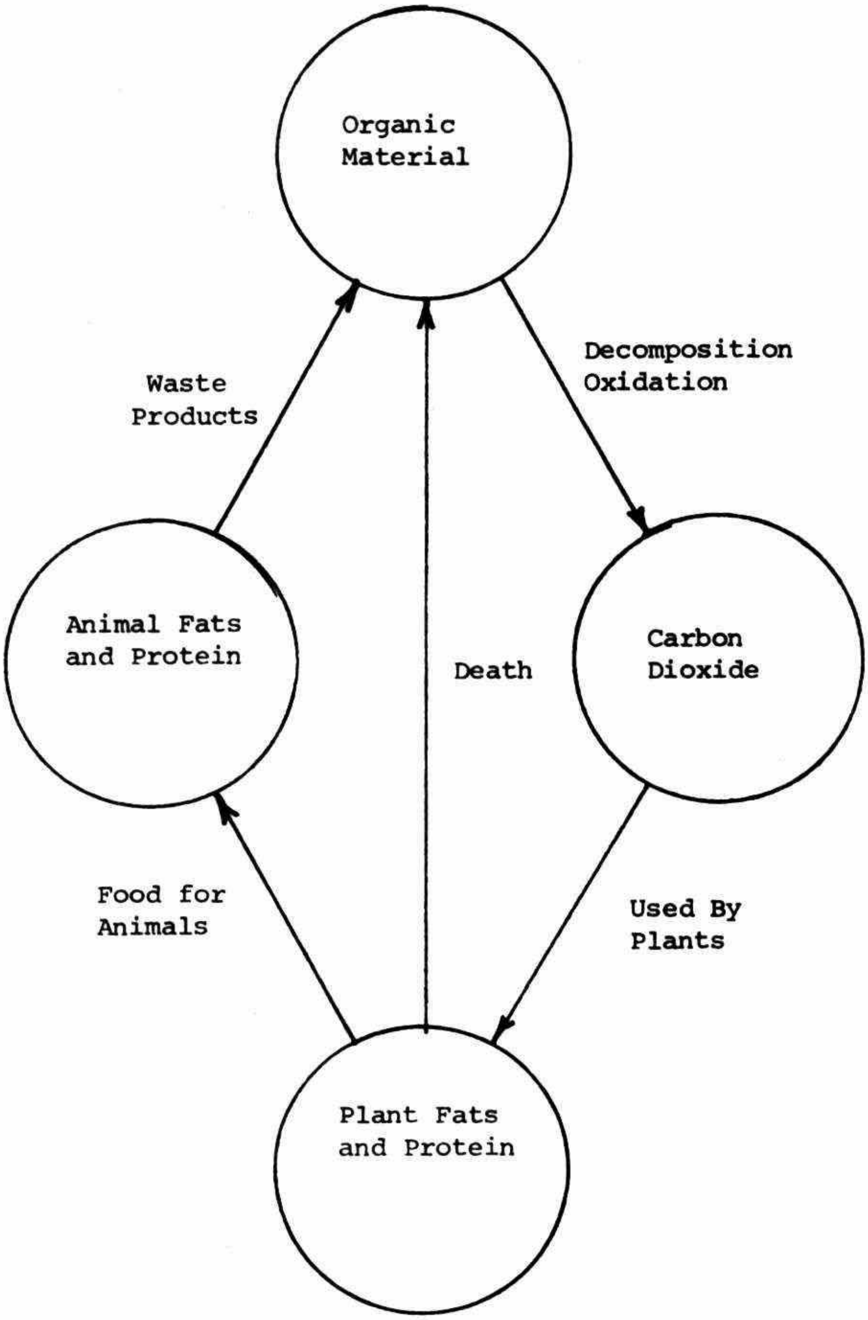
$$\text{Organic Carbon} + \text{Oxygen} \xrightarrow{\text{Bacteria}} \text{Carbon Dioxide} + \text{Water} \qquad (1)$$

Since carbon dioxide is a gas and passes off, one result of the system is then to remove carbon, which can be monitored routinely as five-day BOD (BOD_5) reduction. In order for carbon removal to occur, a population of healthy heterotrophic bacteria must exist in the plant aeration basin. For efficient treatment, their numbers must be maintained proportionate to the weight of the influent waste. This is accomplished by controlling the food-to-microorganism (F/M) ratio. This ratio is expressed as follows:

$$F/M = \frac{\text{wt. of } BOD_5 \text{ (Food) Applied to Aeration Basin per Day}}{\text{wt. of Volatile Suspended Solids (Bacteria) in the Aeration Basin}} \qquad (2)$$

FIGURE 1

CARBON CYCLE



Not all of the carbonaceous material is converted to carbon dioxide, a portion is utilized for cellular maintenance of bacteria and other biota. These biota in turn secrete substances among which are natural polymers. Polymers help in coagulation and flocculation of particles which then can be settled in a secondary clarifier.

The production of biological floc constitutes a continuous gain in insoluble matter (sludge) which must be removed (wasted) from the process to control F/M ratio. These excess solids (waste activated sludge) are then treated further , most often in an aerobic or anaerobic digester, prior to land disposal.

2.2 Nitrogen Cycle and the A/S System

As shown in Figure 2, a cycle also exists in nature for nitrogenous matter (nitrogen compounds). The pathway that can be accommodated by the activated sludge system is that of nitrification, the oxidation of ammonia to nitrite and nitrate nitrogen compounds.

Influent ammonia concentration will normally vary diurnally between 5 and 25 mg/L. Raw wastewater also contains both dissolved and particulate forms of organic nitrogen. The soluble portion may convert to ammonia by hydrolysis in the aeration basin when certain process conditions exist.

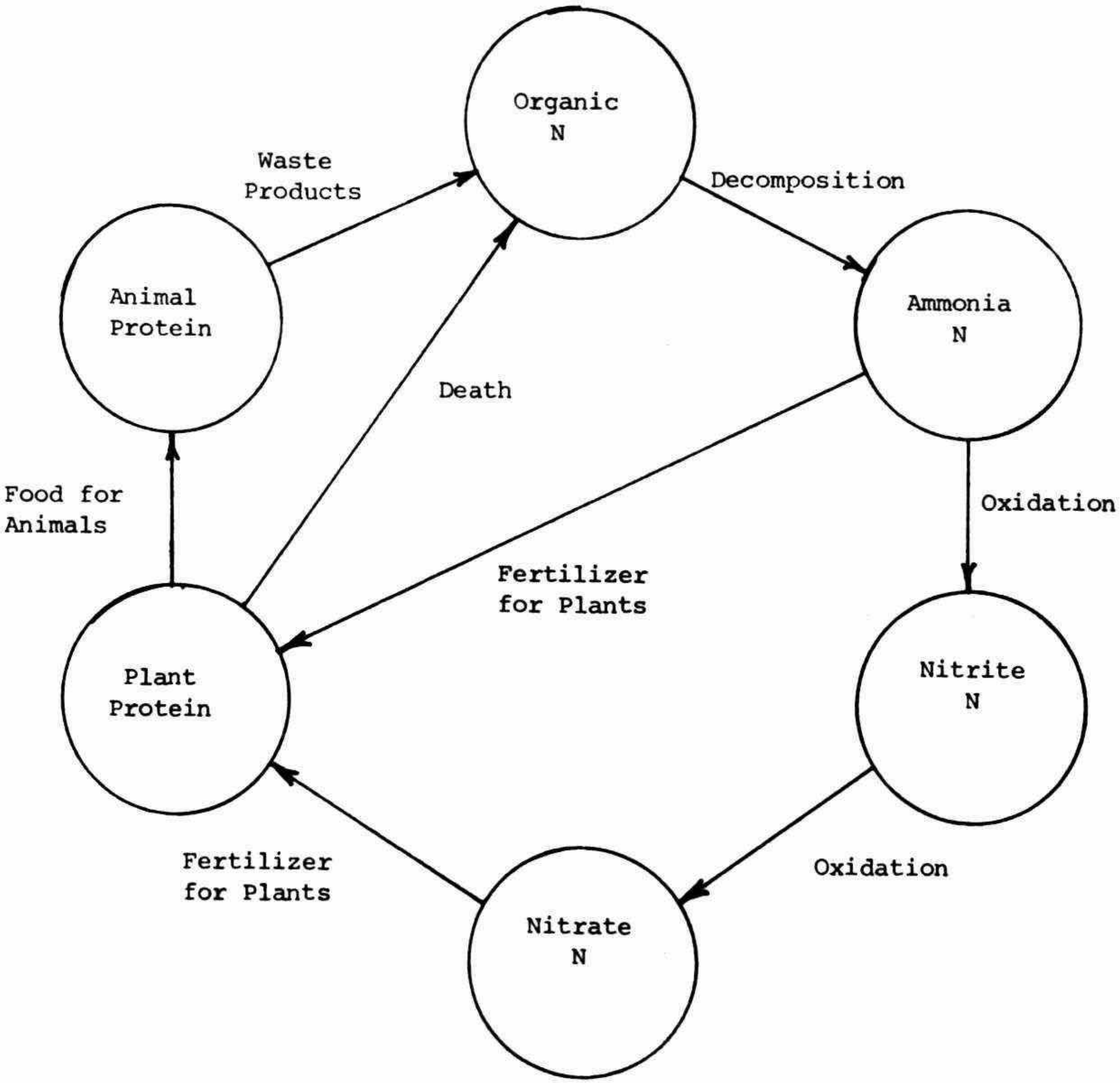
Nitrification, also referred to as nitrogenous oxidation, will occur in the aeration basin, to some degree, in most A/S plants. Two genera of autotrophic bacteria, Nitrosomonas and Nitrobacter, are responsible for nitrification. Their roles are expressed as follows:

$$\underset{\text{Ammonia}}{(NH_4^+)} + \underset{\text{Oxygen}}{(O_2)} \xrightarrow{\text{Nitrosomonas}} \underset{\text{Nitrite}}{(NO_2)} \qquad (3)$$

$$\underset{\text{Nitrite}}{(NO_2)} + \underset{\text{Oxygen}}{(O_2)} \xrightarrow{\text{Nitrobacter}} \underset{\text{Nitrate}}{(NO_3)} \qquad (4)$$

FIGURE 2

NITROGEN CYCLE



Through their metabolism, Nitrosomonas oxidize ammonia to nitrite, then nitrobacter in turn convert nitrite to nitrate nitrogen; this being the final product. Inorganic , as opposed to organic carbon, is utilized by these bacteria as a carbon source and a relatively small sludge production results.

A high degree of both nitrogenous and carbonaceous oxidation can take place simultaneously in the A/S system depending on process conditions.

3. FACTORS AFFECTING NITRIFICATION IN A/S SYSTEMS

1. Temperature
2. F/M Ratio and Volumetric Loading
3. Carbon-to-Nitrogen Ratio
4. Aeration DO
5. Aeration pH and Alkalinity
6. Toxic Substances
7. Solids Retention Time (SRT)
8. Sludge Recycle Rate

To obtain nitrification, limits must be placed upon these parameters to maintain adequate numbers of nitrifying bacteria. These are discussed as follows:

3.1 Temperature

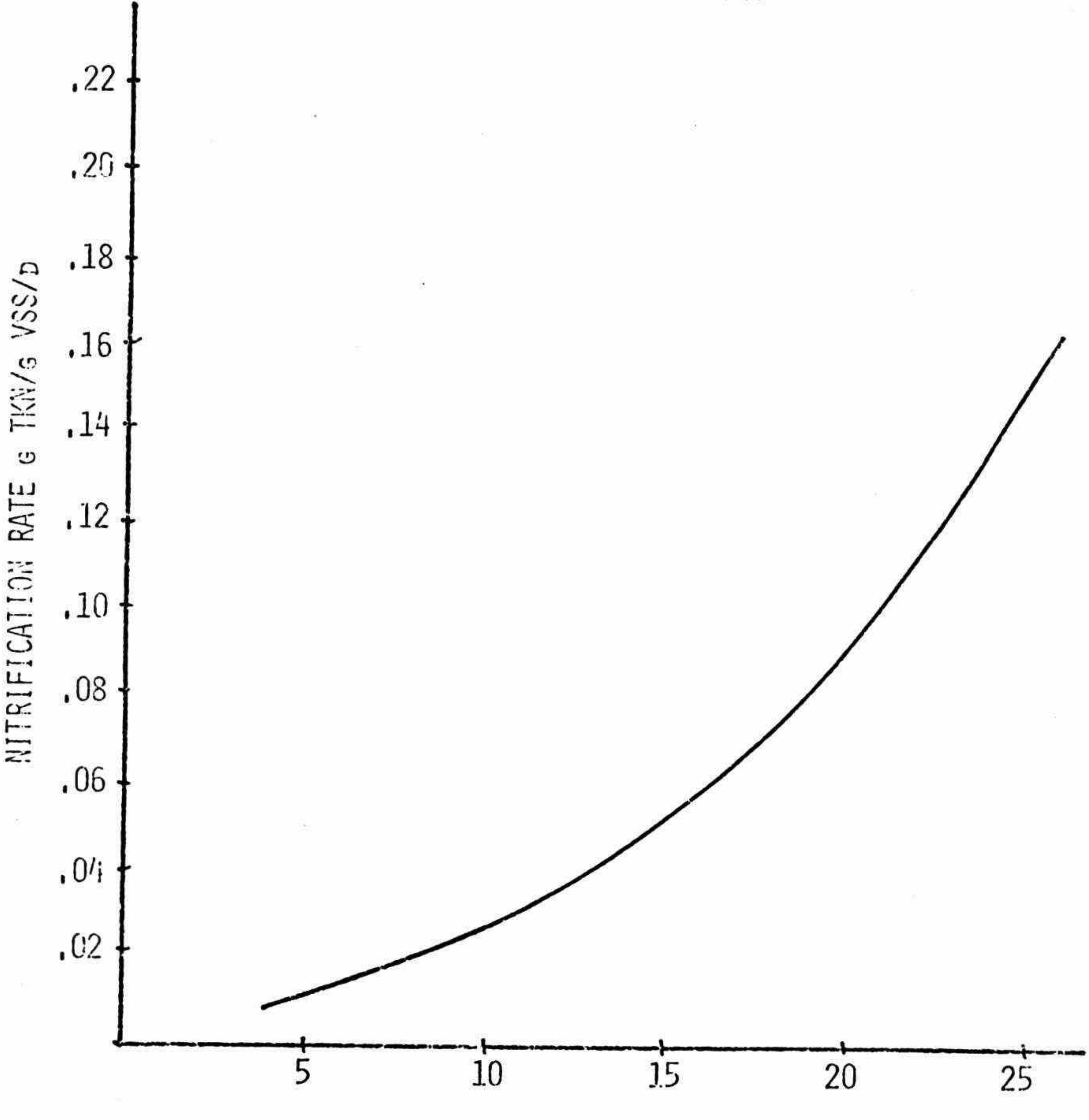
Temperature affects the growth rate of all wastewater bacteria. A low temperature will reduce growth rate and thus make it more difficult to maintain a population in the A/S system.

Heterotrophic (carbonaceous) bacteria double their number approximately every 30 minutes, whereas autotrophic (nitrogenous) types reproduce only every 10-12 hours. Generally, efficient BOD reduction can be maintained in Ontario A/S plants under a wide range of temperatures. However, as shown in Figure 3, nitrification rate is reduced considerably as temperatures drop from 25 to $5^{o}C$. The chance of nitrification occurring in an A/S system during the winter is therefore much less than for BOD reduction. Some operational procedures can be taken to counter the effects of temperature and these will be discussed later.

FIGURE 3

NITRIFICATION RATE
VS
TEMPERATURE

(After Knowles et al (3))



3.2 F/M Ratio and Volumetric Loading

Food-to-microorganism (F/M) ratio or organic loading has been traditionally used as a design parameter for A/S systems. Full nitrification will normally be attained on domestic wastewater at a F/M ratio of less than 0.2 lbs BOD_5 applied/lb aeration VSS/day. In Figure 4, a wide F/M range (up to 0.4) for nitrification is shown, but this includes loadings (0.2 to 0.4) where only onset or partial ammonia oxidation would occur (4). Consistent year-round nitrification will result (depending on wastewater characteristics) with organic loadings approaching the total oxidation (extended aeration) range.

Similarly, there is an upper volumetric loading (wt BOD_5 applied/aeration volume/day) limit at which complete nitrification may be achieved. This value has been determined as:

<20 lb BOD/1000 ft^3/day (<320 g BOD/1000 m^3/day)

3.3 Carbon-to-Nitrogen Ratio

Influent wastewater carbon-to-nitrogen (C/N) ratio influences the relative quantity of nitrifiers to other bacteria, in the aeration basin. Carbon-to-nitrogen ratios have been expressed as BOD_5/TKN (Total Kjeldahl Nitrogen*), BOD_5/NH_3 or with Chemical Oxygen Demand (COD) in place of BOD_5. A range of between 3 to 10 BOD/TKN ratio can be expected in most domestic wastewaters (MOE Plant Records).

The BOD_5 (carbonaceous) fraction will be metabolized first by the heterotrophic bacteria and nitrifiers will not sufficiently populate the aeration basin for nitrification until the BOD_5/TKN ratio is <2 (5). Competition from the heterotrophs will lessen with lowered BOD_5/TKN ratio, as their numbers decrease. Table 1 illustrates

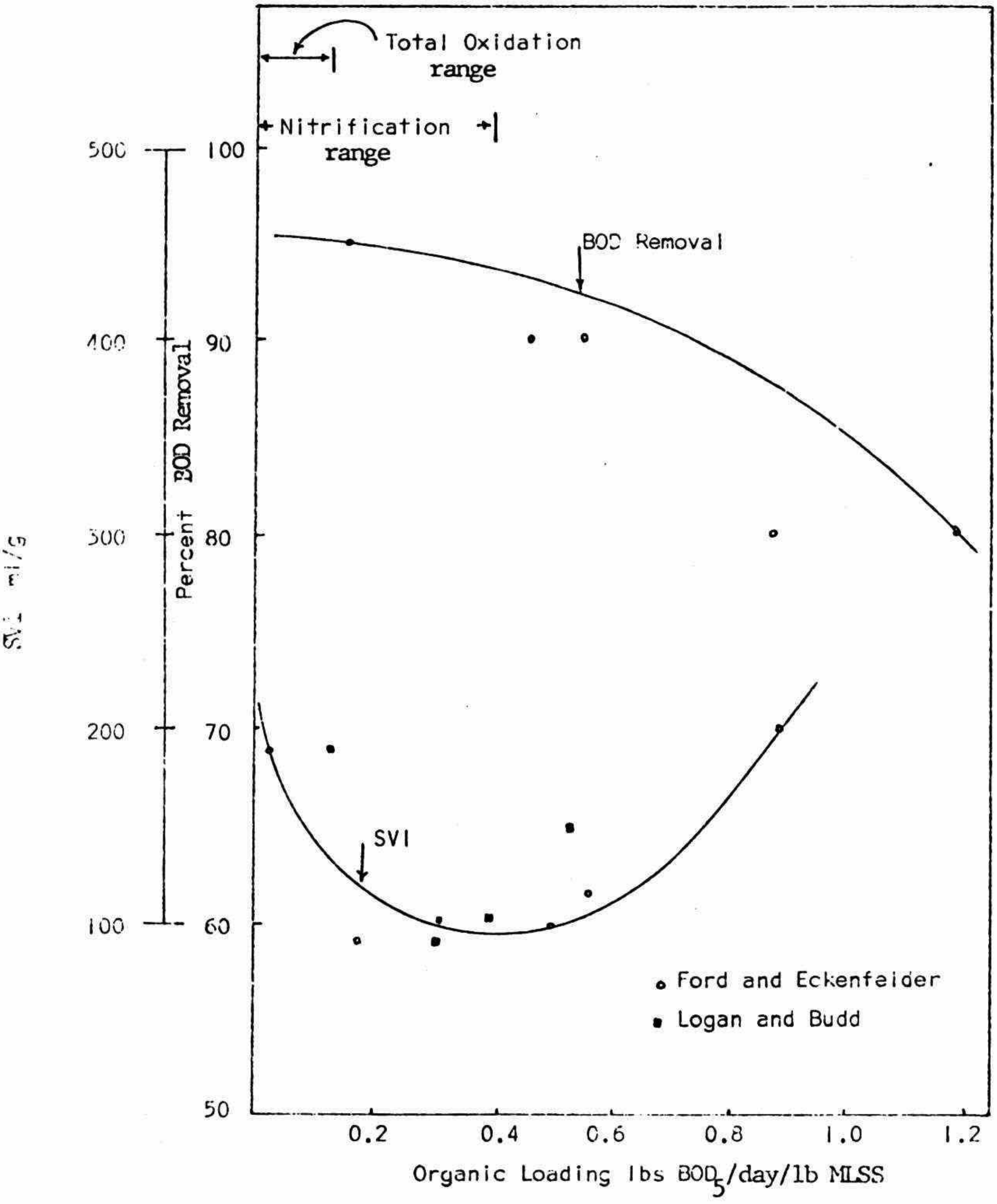
---

* Total Kjeldahl Nitrogen analysis includes both organic and ammonia-N components.

FIGURE 4

EFFECT OF ORGANIC LOADING ON PROCESS EFFICIENCY

(UNIVERSITY OF TEXAS) (4)



the relationship between BOD_5/TKN ratio and predicted nitrifier fraction. In essence, the nitrification rate is increased by reducing the C/N ratio.

3.4 Aeration Dissolved Oxygen

Theoretically, 1 lb of oxygen will be required to oxidize 1 lb of BOD_5 applied to the system. However, an additional 4.6 lbs will be needed for every lb of ammonia applied to a conventionally loaded (BOD_5) A/S system. If a system is designed or operated in the extended aeration range of loading (<0.1 F/M), at least part of the influent organic nitrogen will by hydrolyzed to ammonia. The oxygen requirement will then be based on influent TKN to include the organic fraction.

Aeration oxygen concentration is critical, as a minimum of 2 mg/L should be maintained in all areas of the basin. Experiments have shown that nitrification rate increases significantly upon raising DO from 1 to 2 mg/L and then tapers off at higher concentrations (6) (Figure 5).

3.5 Aeration pH and Alkalinity

Normally, an aeration mixed liquor pH range of 6.5 to 8.5 is required to maintain heterotrophic bacteria and provide BOD_5 removals. A somewhat narrower range is recommended for nitrification.

As illustrated in Figure 6, the percent of maximum nitrification rate is optimum at about pH 8.3 (5). In most cases, this optimum value will not be required for full nitrification in a plant. A suggested operational pH range is 7.0 to 8.3.

TABLE 1

RELATIONSHIP BETWEEN NITRIFIER FRACTION AND THE BOD_5/TKN RATIO

(USEPA Manual (5))

BOD_5/TKN Ratio	Nitrifier Fraction	BOD_5/TKN Ratio	Nitrifier Fraction
0.5	0.35	5	0.054
1	0.21	6	0.043
2	0.12	7	0.037
3	0.083	8	0.033
4	0.064	9	0.029

EFFECT OF DISSOLVED OXYGEN ON NITRIFICATION RATE

FIGURE 5

After Nagel and Haworth (6)

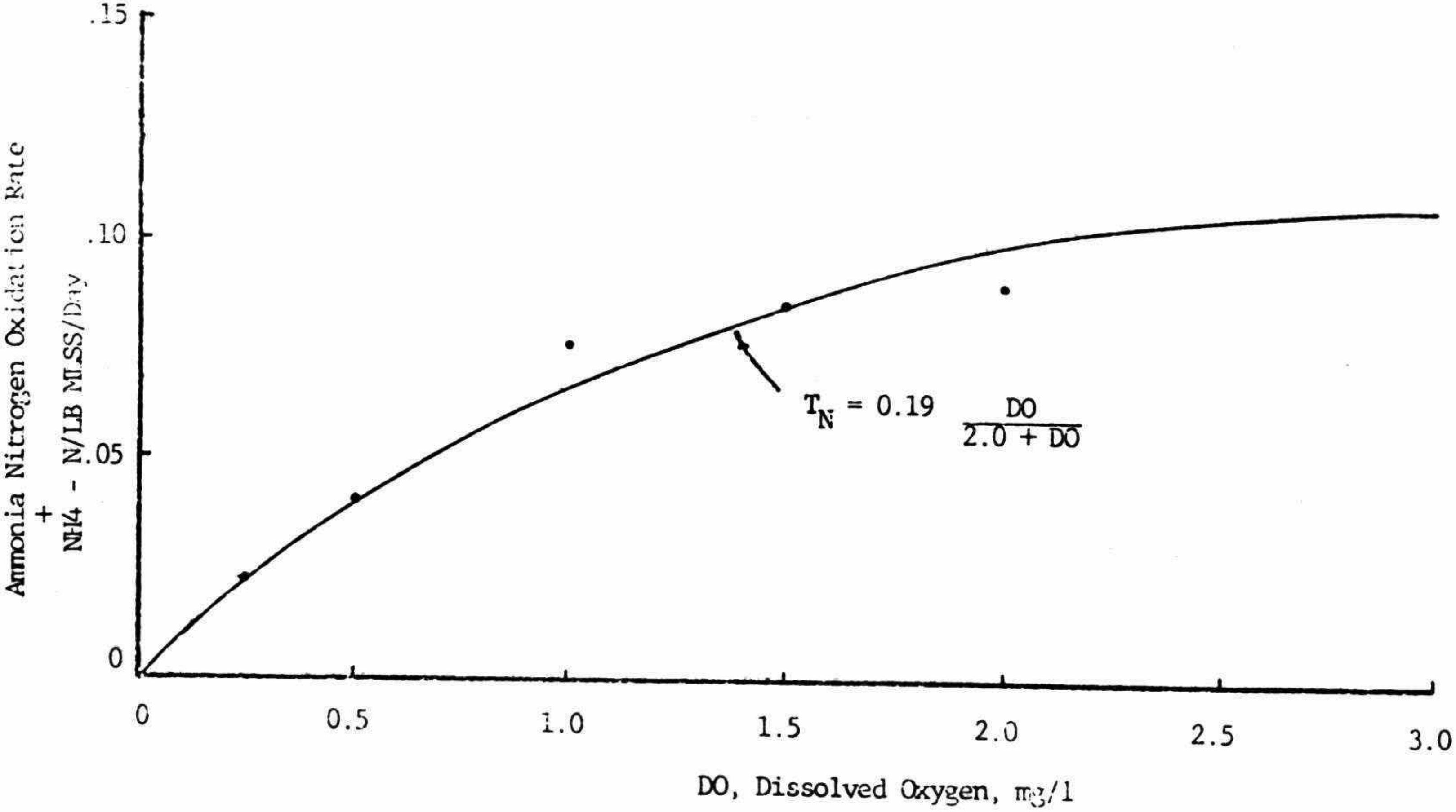
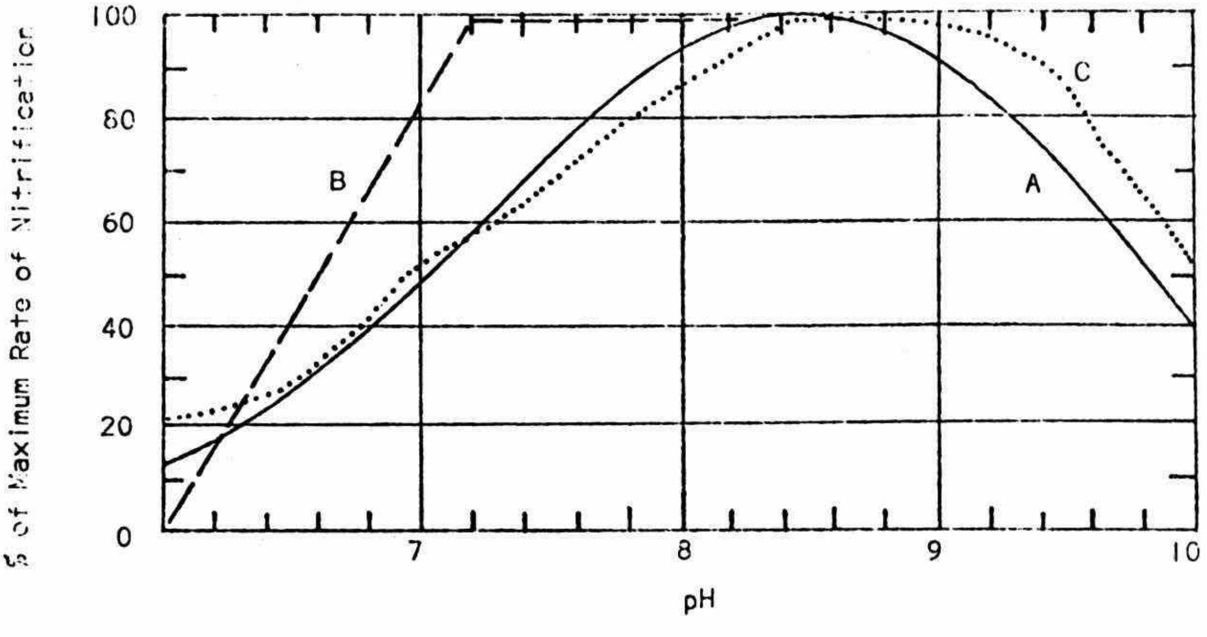


FIGURE 6

EFFECT OF pH ON NITRIFICATION RATE

(U.S.E.P.A. Manual) (5)



A	activated sludge at 20°C
B	activated sludge
C	attached growth reactor at 20°C (i.e. Bio-contactor unit)

For every lb of ammonia oxidized, 7 lbs of calcium alkalinity are removed from the system (5). If either alum or ferric chloride is used for phosphorus removal, an additional loss of 2 to 3 lbs of alkalinity per lb of metal applied will result through phorphorus precipitation reactions (7).

A higher utilization of alkalinity will result when nitrification and/or phosphorus removal is incorporated in the A/S system. If this demand is not met by influent wastewater alkalinity, a drop in aeration pH below 7 will occur causing lowered nitrification rate. Usually if 50 mg/L of $CaCO_3$ alkalinity is maintained in the plant secondary effluent, an aeration pH above 7 will result.

3.6 Toxic Compounds

There are a number of compounds which are toxic to activated sludge bacteria. Nitrifier populations are particularly susceptible because of their relatively low growth rate. Recovery of nitrification will therefore lag that of BOD removal following a toxic kill.

Toxic compounds are found in any of the following forms:

(i) Metallic
(ii) Organic
(iii) Oxidizing

Heavy metals, particularly in the soluble form, are toxic to nitrifiers. One exception appears to be copper, which can also cause toxicity in the insoluble form upon adsorption on the aeration mixed liquor (8).

A variety of organic compounds such as phenol and o-cresol offer toxicity at a variety of concentrations (9).

Oxidizing substances such as chlorine and hydrogen peroxide can have an adverse effect on nitrification, such as when they are used to treat a bulking sludge (10). Some of the substances and their toxic levels are presented in Table 2.

3.7 Sludge Age and Solids Retention Time

The length of time that biological solids spend in the A/S system will have a bearing on ultimate nitrification efficiency. By keeping solids, and thus bacteria, in the system, compensation for low nitrifier growth rate can be accomplished.

The retention period, expressed in days, has been traditionally referred to as Sludge Age (S.A.). There have been a number of S.A. formulae proposed in the past, but that suggested by Gould (11) is most commonly used. It is expressed as follows:

$$\underset{\text{(days)}}{\text{G.S.A.}} = \frac{\text{wt. Aeration SS}}{\text{wt. Influent SS/day}}$$

More recently, a new S.A. expression has been recommended, that of Solids Retention Time (SRT) (12).

$$\underset{\text{(days)}}{\text{SRT}} = \frac{\text{wt. Aeration SS}}{\text{(wt. wasted + Effluent SS)/day}}$$

The advantage of using SRT over GSA is that it forces the operator to maintain a stringent solids inventory. This helps to maintain more consistent treatment and provides data for sludge yield calculation. The GSA formula should only be used for evaluating or operating an A/S plant that does not have means to accurately measure wasting rate.

TABLE 2

REPORTED CONCENTRATIONS OF COMPOUNDS TOXIC TO NITRIFIERS

METALS	Concentration (mg/L) (Higher Than)
Copper	0.05
Zinc	0.08
Magnesium and Calcium	50
Cobalt	0.08
Nickel	0.5
Sodium	2000
Organic	
phenol	5.6
o-cresol	12.8
m-cresol	11.4
p-cresol	16.5
Sodium Cyanide	0.65
Oxidizing	
Chlorine	20
Hydrogen Peroxide	25

Note: The effects of oxidizing compounds upon nitrification will depend on point, concentration and duration of application.

By controlling the wasting rate, the SRT can be altered to produce a given nitrification efficiency. As shown in Figure 7, upon raising SRT, considerable improvement will result in ammonia removal at various temperatures. Compensation for the effects of low temperature and toxic substances can be obtained by raising SRT.

Generally, SRT is accepted as the most important design and operational parameter for nitrification.

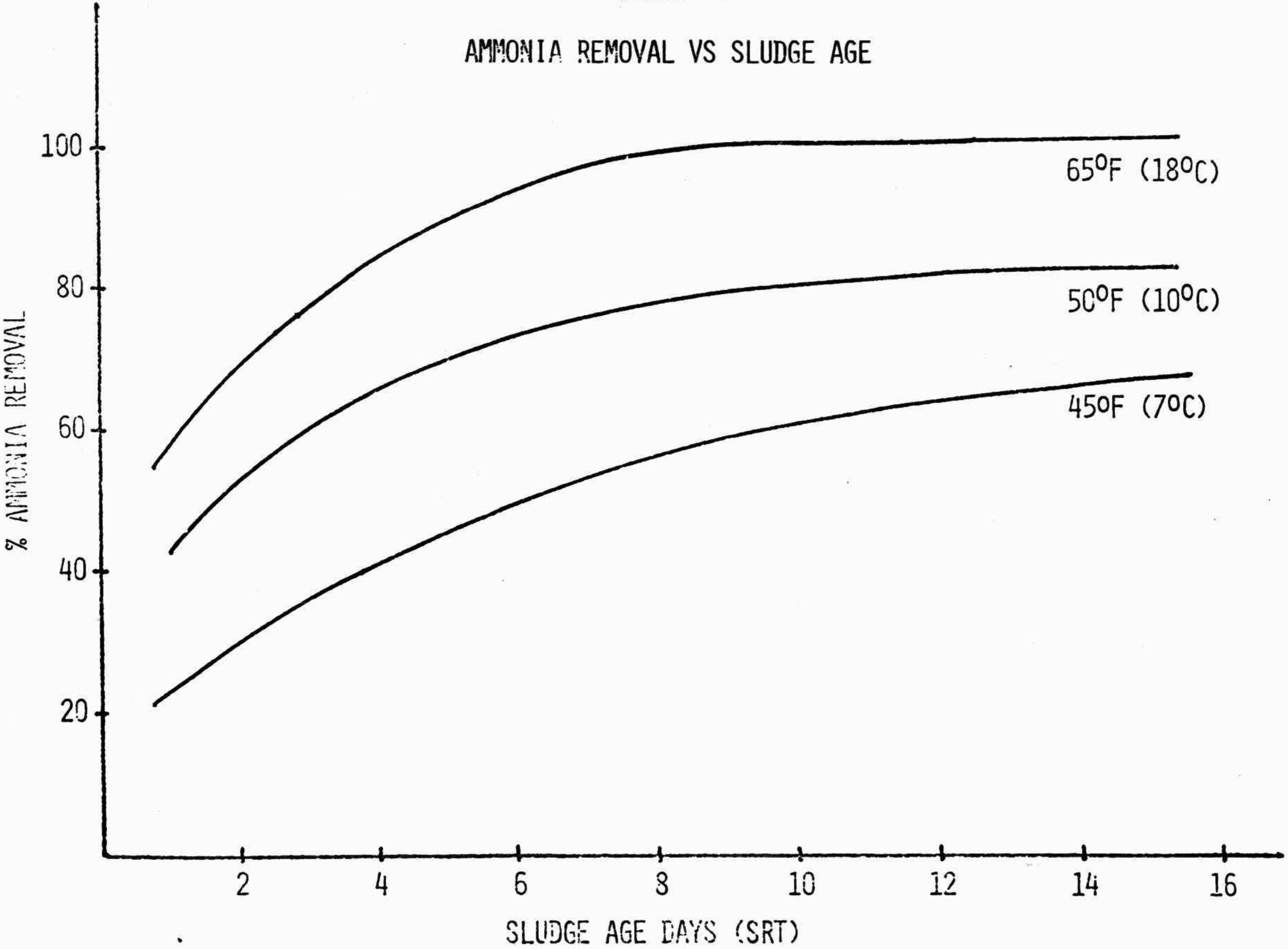
3.8 Sludge Recycle Rate

Sludge Recycle Rate (the rate at which settled mixed liquor is returned to the aeration basin) can influence nitrification. Higher rates (above 50% influent flow) will help maintain a more consistent aeration solids level and thus SRT.

Higher recycle rates will also assist in maintaining a fresh sludge blanket in the secondary clarifier. This will help prevent denitrification (release of nitrogen gas by nitrate conversion) from occurring, which causes surface scum formation and solids carryover.

FIGURE 7

AMMONIA REMOVAL VS SLUDGE AGE



4. SYSTEM CONFIGURATION

An A/S nitrification plant can physically resemble any of the variety of A/S designs currently in operation. The major difference between a facility for carbonaceous removal and one with added nitrification, is the design SRT and loading. However, there are some variations in design which offer advantages to treatment of, and suitability to, certain wastewaters.

4.1 Aeration Basin Design

The shape and wastewater introduction scheme of an aeration basin can influence nitrification efficiency. Four basin configurations are presented in Figure 8.

Example 1 shows the square or "completely mixed" basin. One advantage of this arrangement over others is more efficient mixing and oxygen transfer. Some buffering from toxic waste will also be gained due to uniform dilution throughout the basin. The major disadvantage of this design is the proximity of influent to effluent streams which often causes short-circuiting of untreated wastewater. However, baffling can reduce this occurrence considerably.

Example 2 represents the basin design (semi plug flow*) frequently used in many conventional A/S systems. A rectangular shaped basin produces a more directional flow than the completely mixed arrangement; this in turn limits short-circuiting.

The disadvantage of this design for nitrification is the effects of loading on the first half of the basin. Most of the oxygen demand results there, possibly causing DO sags below 2 mg/L and reduced nitrification rate. Furthermore, less immediate dilution of wastewater at the basin entrance is offered by this configuration, exposing bacteria to higher concentrations of toxic materials than in a completely mixed basin.

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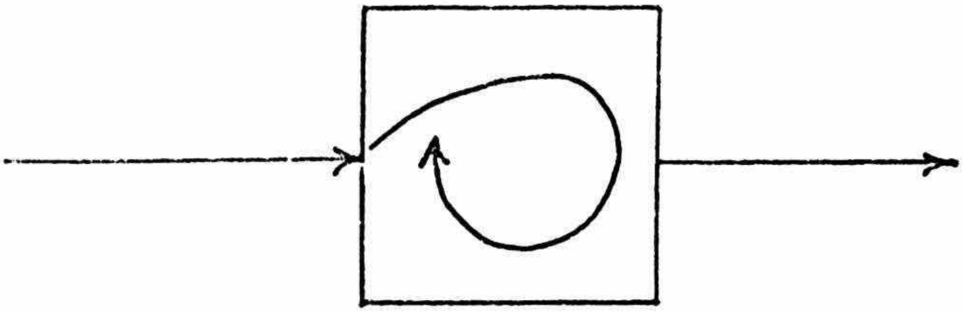
* Plug flow is defined as the situation where wastewater enters a system and continues in one direction to the effluent.

FIGURE 8

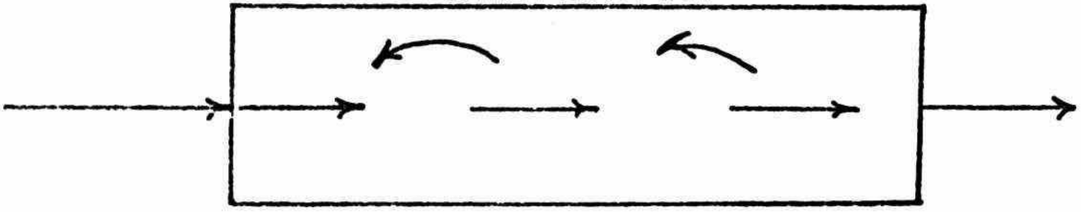
NITRIFICATION BASIN ARRANGEMENTS

COMPLETELY MIXED



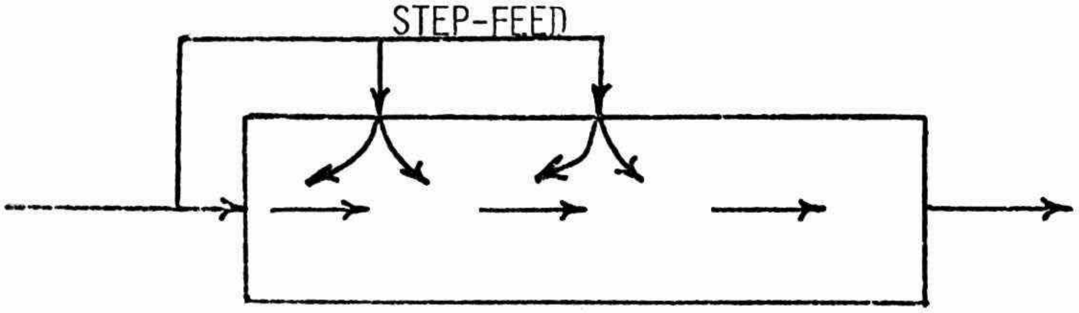
1

SEMI PLUG-FLOW



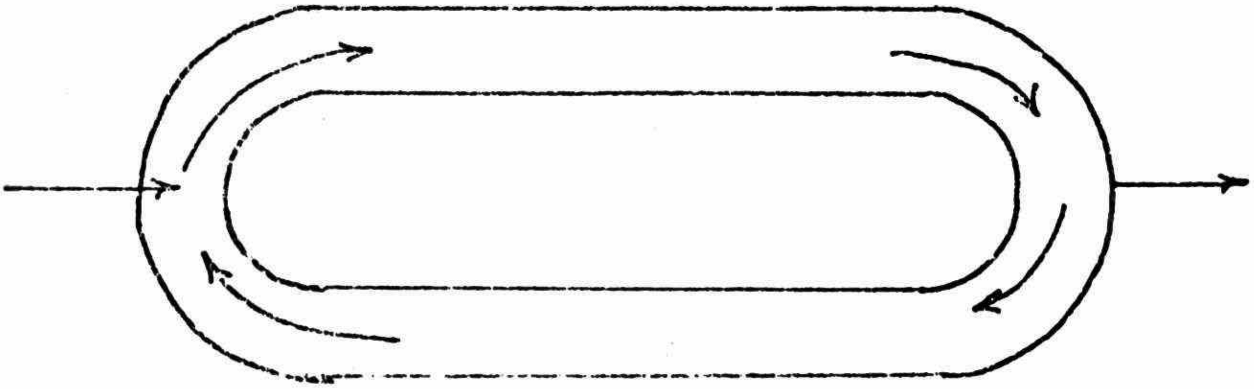
2

STEP-FEED



3

PLUG-FLOW



4

By introducing step feeding to a semi plug flow system as illustrated in Example 3, more uniform waste dispersion will be obtained. This will prevent oxygen sag in the front end of the basin and will offer more dilution to toxic materials.

Basin design Example 4 is the one used for an oxidation ditch. This shape produces conditions of plug flow in which little or no backmixing occurs. Oxidation ditches are usually designed for the extended aeration mode and due to inherent long SRT, this system produces full nitrification and better protection from toxic materials.

4.2 Single and Two Sludge Systems

Either single or two sludge A/S systems can be utilized for nitrification (13). The major difference between these systems is that in the two-stage arrangement, carbonaceous and nitrogenous oxidation take place in separate basins. This separation is accomplished by placing a clarification stage and sludge recycle system between each basin. In the single-sludge system (conventional A/S plant), carbonaceous and nitrogenous oxidation occur in the same aeration tank.

Both arrangements are illustrated in Figures 9 and 10. The advantages of one system over the other are still being disputed. However, the two sludge plant will offer separate control over carbon and nitrogen reactions. The two-sludge configuration may be more suited to industrial wastewater treatment, where some buffering to toxic or high organic constituent, can be afforded in the first stage. However, the cost and operator attention will be more than for a single-sludge facility.

Note: For a more complete discussion on Nitrification, the reader is referred to MOE Research Publication, "Nitrification in Activated Sludge Plants - Guidelines on Some Operation and Design Aspects", (7).

A summary of the guidelines are presented in Appendix A of this manual.

FIGURE 9

SINGLE-SLUDGE SYSTEM

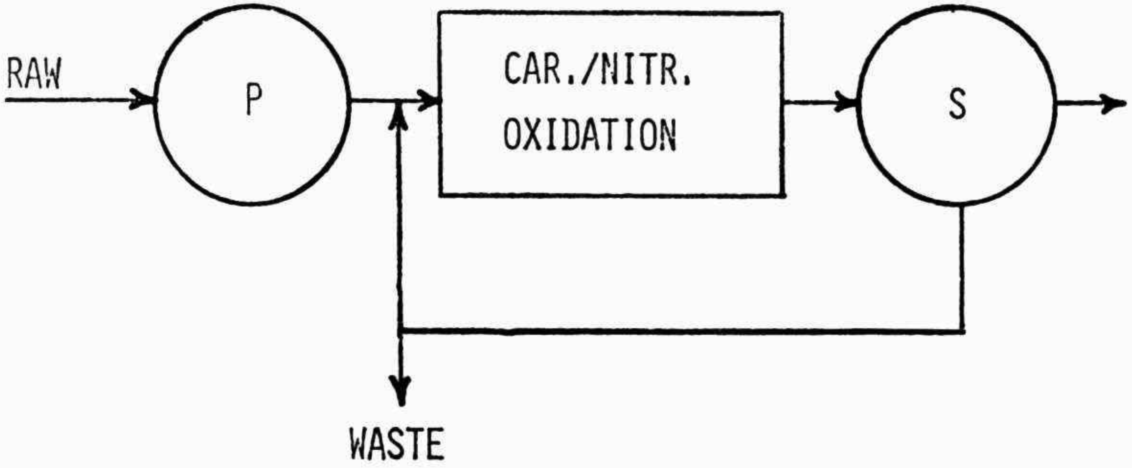
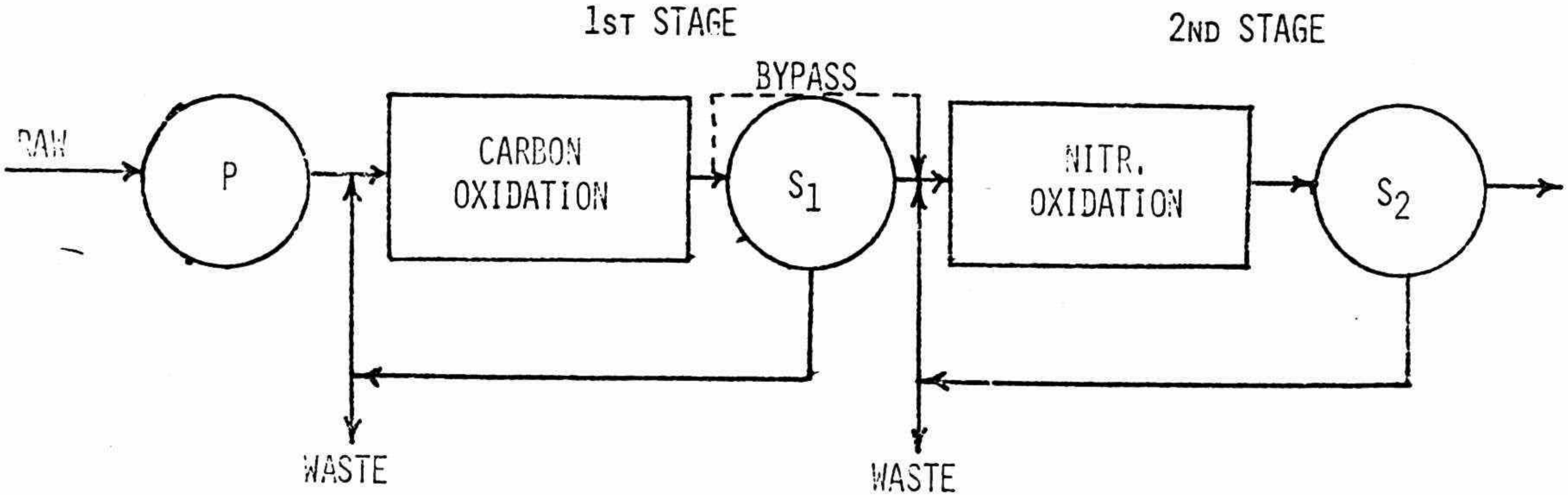


FIGURE 10

TWO-SLUDGE SYSTEM



5. CONTROL AND MONITORING OF THE NITRIFICATION SYSTEM

Because of more stringent effluent criteria, a nitrification facility will have to be controlled and monitored closely. A carefully controlled process SRT should result in lower and more consistent effluent ammonia and TOD. Frequent monitoring of influent and effluent constituents and in-process conditions will assist in facility operation.

Chemical analyses of properly sampled and preserved wastewaters will aid in establishing accurate historical data for the facility. This data will be invaluable reference material if and when a future plant expansion is proposed.

5.1 Major Operational Controls

The five main activities for process operation are as follows:

- maintain balance of system solids
- maintain balance of aeration DO
- limit clarifier loading
- monitor carbon, nitrogen and flow
- examine aeration mixed liquor microscopically

a) System Solids Balance

A balance between aeration and wasted and effluent solids should be maintained using the SRT calculation. For example, by knowing aeration suspended solids concentration and basin volume, the system solids weight can be calculated. By measuring the flow and concentration of the waste activated and secondary effluent stream, the system solids loss can be determined. By adjusting the waste rate (lb/TS day), the aeration solids concentration can be varied thereby controlling SRT. This will be illustrated later.

Many plants do not have the facility to meter waste sludge at low rate continuously. To ensure stability of process solids and nitrification efficiency, this capability is mandatory. Most waste systems can be upgraded inexpensively by installing an in-line meter or an external weir. Timer-operated or special non-clog valves can be installed to regulate waste flow. One method of upgrading a wasting system is offered in a recent MOE Technical Bulletin (14).

b) Aeration DO

Surveys should be conducted along the length of the aeration basin to check for oxygen depletion preferably in the p.m.. Any area having a DO of less than 2 mg/L will normally have less that optimum nitrification rate. Low DO will normally occur in the first half of a rectangular basin diurnally at peak flow periods. To correct this situation, portioning of flow, as outlined in Section 4.1, is recommended to even out basin oxygen demand. An alternative procedure would be to apply more air to the front end of the basin.

c) Clarifier Loading

Since suspended solids contain nitrogenous material (as organic nitrogen), low levels (<15 mg/L) should be maintained in the secondary effluent, particularly if the effluent target is based on TKN. Low effluent solids generally can be assured by limiting secondary clarifier loading.

As outlined in the guideline report (7), certain limits on clarifier loading are recommended, the most important being solids loading. A value of <25 lbs $SS/ft^2/d$ is recommended at peak dry weather flow (PDWF).

For the most part, wastewater flow cannot be regulated so aeration MLSS concentration will be the controlling factor.

5.2 Monitoring

a) Carbon, Nitrogen and Flows

A nitrification system is sensitive to influent carbonaceous and nitrogenous loading, hence frequent composite sampling and analyses of aeration influent should be implemented. This will indicate normal variations in loading and any significant trends in BOD_5, ammonia and TKN concentrations. This information, together with flow data, will show whether the facility is being loaded at above or below design, and is used to evaluate process efficiency. Oxygen requirements for future expansion can also be calculated using this data.

All A/S plants will have flow monitoring equipment, but it is important that devices be calibrated regularly to ensure that true and accurate hydraulic information is obtained.

Similarly, the effluent analyses of these components will show carbon and nitrogen discharge to the receiving water, thereby providing information for regulatory authorities. Regular effluent analyses of nitrogen compounds will also reveal process conditions as a guide for the SRT adjustment, etc.

If nitrogen bacteria are being adversely affected, a change in effluent nitrogen distribution will be noted. For example, a typical municipal influent will contain 20 mg/L of ammonia nitrogen. The resultant effluent nitrogen concentrations of a conventionally loaded nitrification system will be as follows:

Ammonia-N - $\leq$ 1 mg/L
Nitrite - $\leq$ 1 mg/L
Nitrate - 15-18 mg/L

There will usually be a 10 to 15% loss of soluble nitrogen to the maintenance of bacterial cells. Therefore, effluent soluble N will not always match influent values. If oxidized nitrogen concentrations are higher than influent ammonia, some organic-N is probably being hydrolyzed to ammonia in the aeration basin.

If conditions adverse to bacterial growth prevail in the aeration basin, then the nitrobacter will be affected first. This will cause an accumulation of nitrite and a lowering of effluent nitrate-N concentration. Ammonia may remain low so this measurement (NH_3-N) alone will not truly indicate nitrification efficiency. Periodic analyses of nitrite and nitrate-N are necessary to indicate whether nitrogenous oxidation is complete.

If the system TOD discharge is to be calculated regularly, then a ratio of effluent BOD_5 to BOD_{20} (R factor) plus TKN should be determined.

The formula for calculating TOD is as follows:

$$\begin{aligned} TOD &= NOD + CAR\ BOD \\ &= 4.57 \times TKN + R \times BOD_5 \end{aligned}$$

$$\text{where } R = \frac{BOD_{20}}{BOD_5} \quad \text{(Carbonaceous BOD only)}$$

The reader is directed to Appendix B for procedures on the carbonaceous BOD_{20} test.

b) Microscopic Observations

As outlined in the Ministry's Activated Sludge Manual (15), there are benefits from regular observation of aeration mixed liquor protozoa. The presence of toxic materials can often be shown by the *condition and/or types of these life forms. Furthermore, a well operated plant will normally produce certain protozoa and a major diversion from these usually indicates a change in waste characteristics.*

The author has observed a connection between sludge age and expected protozoan types. Systems with longer S.A. such as nitrification plants, cultivate colonial ciliates such as opercularia; rotifiers are often numerous as well. Close examination showing dead or deformed bodies of these forms can indicate toxicity.

5.3 Recommended Schedule of Sampling and Analyses

(a) Sampling

- *grab or grab/composite of aeration and waste activated mixed liquor; minimum 3 days/week;*
- *composites (24 hr) of aeration influent and secondary clarifier effluent; minimum 3 days/week;*
- *raw sewage should be composited once/week if primary clarification is provided.*

(b) Analyses and Tests on Sample Days

Primary effluent - *BOD_5, TKN, NH_4-N, SS, (Total and Soluble P if phosphorus removal is required*

Aeration & WAS - *suspended and volatile suspended solids*
- *1/2 hr settling on aeration*
- *microscopic on aeration ML*

Secondary Effluent - same as primary effluent. In addition, nitrite and nitrate - minimum of 1 day/week

- BOD_{20} either on-site or sent to outside laboratory if TOD calculation is required.

Note: More frequent sampling and analyses than the aforementioned will be required to maintain nitrification through periods of process upset. The laboratory equipment required for on-site analytical monitoring of a nitrification plant are presented in Appendix C.

5.4 Using Data for Process Control

As stated earlier, SRT is the most important operational parameter for a nitrification plant. The wasting rate (mass SS/day) can be varied to maintain the optimum SRT to achieve a desired effluent ammonia. Normally, a 10-day SRT will require wasting 10% of the aeration solids by weight/day, although this relationship may not hold true for all plants. An example problem is illustrated as follows:

PLANT DATA

Aeration volume - 500,000 gals (2273 m^3)

Aeration MLSS - 1446 mg/L

WAS SS - 3600 mg/L

WAS Flow - 52,400 g/d (238 m^3/d)

Sec. Effl. SS - 15 mg/L

Plant Flow - 1.4 MIGPD (6364 m^3/d)

Influent SS - 104 mg/L

i) Calculate SRT (days)

$$SRT = \frac{1446 \times 0.5 \times 10}{(3600 \times 0.0524 \times 10) + (15 \times 1.4 \times 10)}$$

$$= \frac{7230}{1886 + 210}$$

$$= \underline{3.4 \text{ days}}$$

Note: In this case, the wasting rate represents 26% of aeration solids weight.

ii) Calculate the Gould Sludge Age using data from problem (i)

$$G.S.A. = \frac{1446 \times 0.5 \times 10}{104 \times 1.4 \times 10}$$

$$= \frac{7230}{1456}$$

$$= \underline{5 \text{ days}}$$

A process SRT of 3.4 days may not be adequate to maintain a low effluent ammonia; the SRT would then have to be increased.

iii) Using the SRT of 3.4 from problem (i), calculate the waste rate required to raise the SRT to 10 days. To increase SRT, the waste rate must be reduced.

New waste rate $= \frac{3.4}{10} \times 1886 = \underline{641 \text{ lbs SS/day}}$ (290 Kg SS/d)

The hydraulic rate (Ig/d) can then be calculated using the WAS concentration.

New hydraulic rate $= \frac{641}{1886} \times 50{,}000$

$= 17{,}000$ gal/day (77 m^3/d)

After the system has adjusted to the new wasting rate, the WAS MLSS will rise with the aeration concentration. Some readjustment of the wasting rate will then have to be made by trial and error.

(iv) *When raising SRT, the solids loading on the clarifier will be increased. The value should be determined to see if it exceeds 25 lbs SS/ft^2/d (PDWF) (122 Kg/m^2/d). Calculate the clarifier solids loading*

Flow - *2.0 MIGPD (PDWF) (9091 m^3/d)*

Aeration MLSS - *4000 mg/L*

Recycle Rate at 80% of Influent - *1.6 MIGPD (5091 m^3/d)*

Clarifier Area - *2800 sq ft (260 m^2)*

$$\text{Clarifier Solids Loading} = \frac{\text{Mass of Solids Delivered to Clarifier/day}}{\text{Clarifier Area}}$$

Clarifier influent flow consists of raw plus recycle flow.

Therefore: Flow to Clarifier = 2.0 + 1.6

= 3.6 IMGPD (16,364 m^3/d)

$$\text{Solids Loading (inc. recycle)} = \frac{3.6 \times 4000 \times 10}{2800}$$

$$= 51 \text{ lb SS/ft}^2\text{/day (249 Kg SS)}$$

Since the clarifier solids loading exceeds the recommended value at PDWF, the clarification stage is the limiting factor in the control of SRT, particularly if effluent solids concentration has risen drastically. In this case, the facility is incapable of operating at a 10-day SRT; a lower value (between 3 and 10) is recommended.

To summarize, the operator should be able to match wasting rate to effluent ammonia concentration, assuming other process conditions are being met. The wasting rate can be seasonally adjusted to compensate for wastewater temperature, loading, etc.

5.5 *Calculating Effluent TOD*

Some nitrification plants will be designed and operated on the basis of allowable mass of effluent TOD discharged per day. Using the following plant data, calculate the TOD concentration and the lbs per day of TOD discharged.

Flow - 8.5 MIGPD

Effluent TKN - 4.5 mg/L

BOD_5 *- 10 mg/L*

BOD_{20} *- 25 mg/L*

$$TOD = NOD + CAR\ BOD$$

$$= 4.57 \times 4.5 + \frac{25}{10} \times 10$$

$$= 46 \text{ mg/L}$$

Therefore: TOD discharged (lbs/day) = 46 x 8.5 x 10

= 3910 lb/d
(1775 Kg/d)

NOTE:

Once an R. factor (defined on p.29) has been established for a WPCP effluent, frequent analyses of BOD_{20} *will not be required. For routine calculation of TOD, the predetermined factor can be used. However, the R factor can vary due to changing effluent characteristics necessitating occasional checks.*

6. OTHER PERTINENT CALCULATIONS

Aside from process control related calculations, there are other computations which will aid in an in-depth evaluation of a nitrification facility. These are as follows:

- *ammonia loading rate*
- *nitrification rate*
- BOD_5 *loading rate*
- *F/M ratio*

As an example, the above are calculated using the following data:

Plant Flow	- 5.0 MIGPD
Aeration Influent BOD_5	- 120 mg/L
Aeration Influent Ammonia-N	- 20 mg/L
Aeration Volume	- 2.5 MIG
Aeration MLVSS	- 1500 mg/L
Secondary Effluent Ammonia-N	- 2 mg/L

a) Ammonia Loading Rate (lbs NH_4-N added/day)

$$= 5 \times 20 \times 10$$

$$= 1000$$

b) Nitrification Rate (lbs NH_4-N removed/lb Aer MLVSS/day)

$$= \frac{(20-2) \times 5 \times 10}{1500 \times 2.5 \times 10}$$

$$= \frac{900}{37,500}$$

$$= 0.024$$

c) BOD_5 (carbonaceous) Loading Rate (lbs BOD_5 applied to aeration/day

$$= 5 \times 120 \times 10$$

$$= 6,000$$

d) *F/M Ratio (lbs BOD_5 applied to aeration/lb Aer. VSS/day)*

$$= \frac{6{,}000}{37{,}500}$$

$$= 0.16$$

7. SITUATIONAL TROUBLESHOOTING DURING PROCESS UPSET

Due to wastewater conditions and/or process functions, nitrification efficiency can deteriorate at any time without any visual change in effluent quality. Only chemical analyses will reveal the extent of lost nitrification. A quick recovery of conditions suitable for nitrifiers is vital due to their low recovery rate. The operations personnel must therefore systematically search out the cause and apply immediate corrective measures.

7.1 Areas of Investigation and Approaches

Usually by raising SRT a decreasing nitrification rate can be stalled and a recovery will result. If further losses in nitrification continue for several days following SRT adjustments, other areas must then be examined. These are as follows:

a) Changes in wastewater characteristics, such as raised BOD_5/TKN ratio, industrial wastes or pH, etc.;

b) Changes in influent flow patterns;

c) Insufficient aeration DO;

d) Chemical addition for phosphorus removal or SVI control.

a) Changes in Wastewater Characteristics

An abrupt rise in wastewater BOD_5, TKN and/or ammonia will impose a higher-than-normal oxygen demand upon the system. This can eventually be substantiated by regular 24-hour composite sampling and analyses; but a more immediate test is required. The oxygen utilization rate test (as outlined in the MOE Activated Sludge Course Manual (15)) can be used as a measure of process loading.

Every A/S process will have a design range of process volumetric loading (lbs BOD_5 applied per 1000 ft^3 aeration capacity). Oxygen utilization rate (mg O_2/L/hr) will normally correlate closely with volumetric loading values. For example, if a nitrification plant is designed to operate in the extended aeration range of loading (5-15 lbs BOD/1000 ft^3/day), then the aeration O_2 utilization values will normally be within this range (5-15 mg O_2/L/hr). Results higher than 15 mg O_2/L/hr. show above design oxygen demand.

An abrupt change in aeration ML (during normal dry weather conditions) such as loss of solids concentrations with surface foaming and a turbid ML supernatant, suggests toxicity. An immediate rise in effluent ammonia will also occur. The WPCP plant and/or regional staff should have a complete and up-to-date file on all the industrial inputs to the plant. Those companies that handle toxic wastes should be contacted immediately to check for accidental spills.

A drop in aeration basin oxygen utilization rate will occur during bacterial upset periods. This observation should be recorded and compared with normal values for the plant as evidence of toxicity.

More frequent measurements of raw wastewater and aeration ML pH should be initiated during a process upset. This will show whether aeration pH is within the optimum range (7.0-8.3) and will help in tracing the source of industrial discharge.

To assist in the recovery of nitrification, wasting should be ceased allowing a buildup of aeration solids, to the point at which the maximum solids loading to the secondary clarifier (25 lbs/ft^2/day) is obtained. This will help in establishing a new nitrifier population. A higher-than-normal SRT should be maintained with low rate wasting, until full nitrification is recovered.

b) Influent Flow Patterns

High flows due to stormwater infiltration can cause at least a partial loss in process nitrification. This will often be due to an abrupt loss of solids, drastically lowering SRT. Unfortunately, there is little or no adjustment that can be made to counteract high flows.

Ideally, all nitrification plants should be preceded by separate storm and sanitary sewers. If this is the case, and storms are still influencing flows, an investigation of sewer conditions is warranted.

The procedure for process reinstatement following a washout from storm flow is similar to that following a toxic kill. Wasting should be ceased during and immediately following the unstable period.

c) Insufficient Aeration DO

As stated in Section 3.4, nitrification rate is highly dependent on aeration DO concentration. When searching for a cause of lowered nitrification efficiency, a survey of the aeration basin is highly recommended. If specific areas of the basin show DO levels lower than 2 mg/L, application of more air and/or less wastewater to these locations (if these options are available) will improve nitrification.

Examination of plant records may reveal that under normal loading and temperature, a gradual decrease in aeration DO has occurred over several months. This suggests that the aeration equipment is at fault. Devices such as blowers or surface aerators should then be inspected for mechanical wear.

Often turbulence patterns of the liquid surface of the aeration basin will reveal areas where there are plugged diffusers or broken airlines; these will prevent adequate oxygen transfer and should be repaired.

d) Phosphorus Removal and SVI Control

Occasionally, plant staff will increase chemical dosage (commonly alum or ferric chloride) to lower effluent phosphorus concentration. A drop in aeration pH (below the optimum range for nitrification) can result from this, if reserve alkalinity is not present in the wastewater. To remedy this, alkalinity (lime or soda ash) will have to be added to the aeration basin influent to maintain a pH above 7. For example, at the Gravenhurst, Ontario plant, dry lime is added to the aeration basin daily to prevent acidity.

In some instances, poor sedimentation may actually be the cause of increased effluent phosphorus. Raising of chemical will then be unwarranted, particularly if effluent soluble phosphorus is ≤ 0.5 mg/L.

If the aeration mixed liquor has a higher-than-normal Sludge Volume Index (SVI), secondary sedimentation will be affected. Most secondary clarifiers are designed for a particular solids loading and/or overflow rate for an SVI below 200 ml/g. Higher SVI will often result in a clarifier sludge blanket of low density, which tends to release solids to the effluent.

If a high SVI is accompanied by profuse growth of filamentous organisms, and solids loss from the system is uncontrollable, chlorination of recycle sludge is justifiable. However, this application should be carefully controlled to ensure continued nitrification (see Section 3.6). Frequent analyses of effluent ammonia during sludge chlorination is important. If a sudden rise in ammonia concentration results, chlorination should be discontinued until full nitrification is regained.

In 1946, Tapleshay (16) published a report outlining procedures for "sludge density control" by chlorination. He recommended that chlorine dosage be governed by SVI and recycle concentration. An illustration of this method from Tapleshay's report is presented in Figure 11. The author has similarly discovered through field tests (unpublished) that by lowering chlorine dosage as SVI decreases, severe process upset can be avoided.

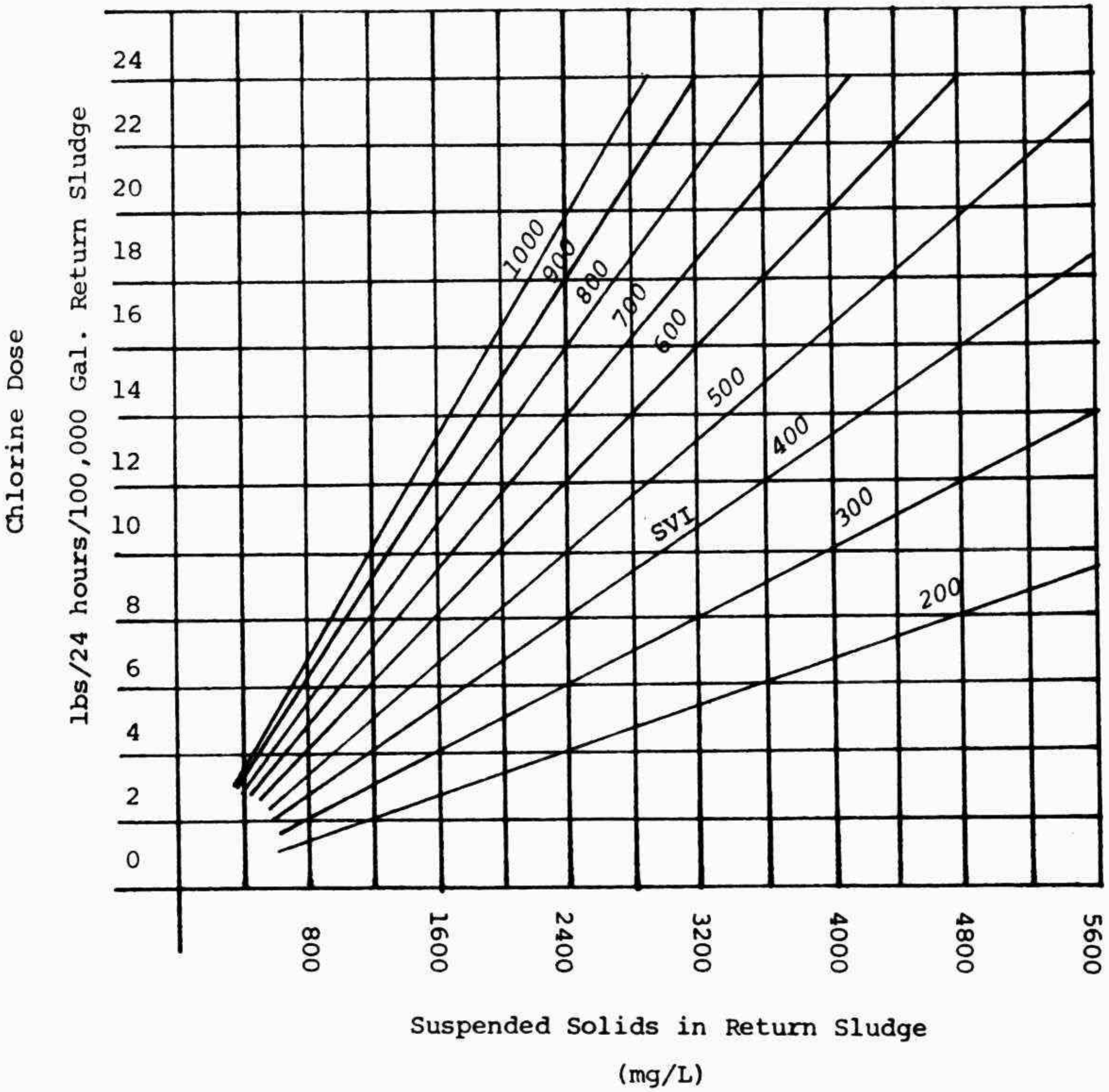
The application of chemical to control SVI in a nitrification system should be avoided if possible due to the sensitivity of nitrifiers. Often the better approach is to allow the system to correct itself, and try to determine the cause of high SVI. The possible causes of high SVI are listed as follows:

1. *Septic influent wastewater (hydrogen sulphide);*
2. *Low influent trace metal concentrations;*
3. *High F/M ratio (above 0.4);*
4. *High influent C/N ratio;*
5. *Low aeration DO (<1 mg/L).*

Figure 11

CHART FOR DETERMINING CHLORINE
DOSAGE TO RETURN SLUDGE FOR
SVI CONTROL

(After Topleshay (16)



8. TREATABILITY STUDIES

For the most part, treatability studies serve to show what SRT is required, using the A/S system, to nitrify a particular wastewater. These studies are particularly useful when a wastewater having some toxic component is to be treated. Normally, longer SRT will be required at all temperatures to counteract toxic effects on nitrification bacteria. This procedure will help maintain an adequate supply of healthy bacteria and allow for adaptation to the wastewater.

The various classifications of treatability studies, such as laboratory, pilot plant and semi-fullscale, are discussed in the nitrification guideline report (7). To assist in operation of an industrial or domestic/industrial nitrification plant, a laboratory scale unit is recommended. These units are miniature A/S systems which can be used as continuous biological indicators. If change in wastewater characteristics occurs, an adjustment in process SRT may be required to maintain nitrification. Operation of one or more laboratory units will assist in finding a new optimum SRT.

For information on how to run treatability studies, the reader is referred to MOE Technical Bulletins #1004 (17) and 1008 (18).

9. SUMMARY

a) Nitrification of wastewater is required to reduce A/S plant discharge of NOD and/or toxic ammonia. Disinfection efficiency will be improved with nitrification.

b) The two major nitrification bacteria Nitrosomonas and Nitrobacter are susceptible to factors such as temperature, C/N ratio and toxic substances.

c) Various system configurations are possible for nitrification with particular advantages or disadvantages specific to each.

d) Operation of an A/S nitrification plant requires control of parameters such as SRT, aeration DO and clarifier solids loading.

e) Upgrading of sludge wasting facilities providing low rate continuous flow is highly recommended for solids control.

f) Frequent sampling and analyses will be required to monitor a nitrification plant. Continuous laboratory A/S units are recommended for biological monitoring when toxic substances are involved.

REFERENCES

1. Ministries of the Environment and Natural Resources (Ontario), Thames River Basin Water Management Study.

2. Smith, A.G., "Nitrogen Removal - An Evaluation of Full-Scale Biological Systems", Proc. Tech. Transfer Seminar on High Quality Effluents, Toronto, Ontario, December, 1975, Info. Can. Cat. # EN 43-12/1976-3, pgs. 289-324.

3. Knowles, G., Downing, A.L. and Barrett, M.J., "Determination of Kinetic Constants for Nitrifying Bacteria in Mixed Culture, With the Aid of an Electronic Computer", J. Gen. Microbiology, 38, p. 263, (1965).

4. University of Texas at Austin, "Advanced Water Pollution Control Biological Waste Treatment", Course Manual, 1973.

5. U.S. EPA, "Process Design Manual for Nitrogen Control", Tech. Transfer Report, 1975.

6. Nagel, C.A. and Haworth, J.C., "Operational Factors Affecting Nitrification in the Activated Sludge Process", 42nd Annual WPCP Conference, Dallas, Texas, October, 1969.

7. Smith, A.G., "Nitrification in Activated Sludge Plants - Guidelines on Some Operation and Design Aspects", MOE Research Publication W62, Revised, July, 1977.

8. Skinner, F.A. and Walker, N., (Heavy Metals), Arch., Mikiobiol., 1961, 38, 339.

9. Loveless, J.C. and Painter, H.A., "The Influence of Metal Ion Concentrations and pH Value on the Growth of a Nitrosomonas Strain Isolated from Activated Sludge", Jn. Gen. Microbiol., 52, 1-14, 1968.

10. Downing, A.L., Tomlinson, T.G. and Truesdale, G.A., "Effect of Inhibitors on Nitrification in the Activated Sludge Process", Jn. Inst. Sew. Purif., 1964, pgs. 537-554.

11. Imhoff and Fair, Gould Sludge Age, Text, "Sewage Treatment", Publisher John Wiley and Sons Ltd., 1966.

12. McCarty, P.L., "Nitrification-Denitrification by Biological Treatment", Univ. of Mass. Correspondence (at home) Conf. on Denitrification of Municipal Waste, March, 1973.

13. U.S. EPA, "Nitrification and Denitrification Facilities", Technology Transfer Seminar Publication, Revised, February, 1974.

14. Smith, A.G., "Automatic Continuous Sludge Wasting System for an Activated Sludge Process", MOE Wastewater Treatment Section, Technical Information Bulletin No. 1007, July 6, 1978.

15. Ministry of the Environment, "Activated Sludge Workshop Manual", Publication of the Training and Certification Section, Pollution Control Branch, 1976.

16. Tapleshay, "Sludge Density Control", Jn. Water and Sewage Works, March, 1946.

17. *Ministry of the Environment, "The Design and Conduct of Toxicity, Biodegradability and Treatability Studies", Technical Information Bulletin #1004, Wastewater Treatment Section, Pollution Control Branch, June 20, 1977.*

18. *Smith, A.G., "Nitrification Treatability Studies Using Model Scale Activated Sludge Units", Ministry of the Environment, Wastewater Treatment Section, Technical Information Bulletin #1008, August, 1978.*

APPENDIX A

PARAMETERS AFFECTING THE NITRIFICATION PROCESS AND SUGGESTED DESIGN RECOMMENDATIONS

1. Waste and Flow Variation	- Flow equalization if peaking factor frequently exceeds 1.5.
2. Aeration pH and Alkalinity	- 6.5 to 8.5 - optimum 8.3 minimum effluent of 50 mg/l as $CaCO_3$
3. Aeration O_2 requirements (based on average daily BOD_5 and TKN). Peaking factor applied to NH_4-N for conventional.	- Nitrogenous - 4.6 lbs O_2/lb NH_4-N-Conventional 4.6 lbs O_2/lb TKN -Extended - Carbonaceous- 0.8 lb O_2/lb BOD_5 -High Rate 1.0 lb O_2/lb BOD_5 -Conventional 1.5 lb O_2/lb BOD_5 -Extended - Minimum DO of 2 mg/l in all areas of the aeration tank.
4. Solids Retention Time (SRT)	- For 1 mg/l effluent ammonia nitrogen > 2 days at 20°C >10 days at 5°C - Safety factor to be determined via treatability studies.
5. F/M Ratio	- 0.05 to 0.25 lb BOD_5/lb MLVSS
6. Secondary Clarifier	
(a) High Rate (First Stage)	- Detention (hrs) - 2.5 - Overflow rate - 1000 Ig/ft^2/day (PDWF)* (49 m^3/m^2/day)
(b) Second Stage or Combined System	- Detention (hrs) - >3.0 hrs - Overflow rate - <600 Ig/ft^2/day (PDWF) (29 m^3/m^2/day) - Solids Loading - <25 lbs/ft^2/day (PDWF) (122 Kg/m^2/day) (including 100% recycle flow). Minimum sidewall depth of 12 ft (3.6 m)
7. Sludge Recycle Rate	- Minimum of 80% of influent flow (ADWF)**

* The average peak 4 hour flow during dry weather.

** The average daily flow expected during dry weather.

APPENDIX B

Carbonaceous BOD_{20} Determination

The method used is the same as that outlined for BOD_5 in Standard Methods, 14th Edition, Part 507. Bacteriological sample bottles (6 oz) with cone shaped, polyseal lined caps have been used successfully by the MOE Wastewater Treatment Section Laboratory.

A wide range of dilutions are taken (5, 7.5, 15, 25 and 50%) to obtain a 40%-70% oxygen depletion and 2 mg/L Allyl thiourea (ATU) is used to inhibit nitrification. Prepare 2 bottles for each sample dilution, one for initial DO and the other for incubation. Before incubation, BOD bottles are filled to overflowing with BOD water to prevent air entrapment. The caps are then tightly secured and bottles are incubated at $20^{o}C$ for 20 days and final DO read. Several blanks of dilution water are incubated and the DO read every 5 days to ensure no oxygen depletion is occurring.

Calculate as for BOD_5.

APPENDIX C

WPCP Laboratory Facilities and Sample Preservation

To facilitate adequate process control, the following lab equipment should be available to the plant staff for on-site analyses:

		Approximate Cost*
1.	Drying oven and muffle furnace for suspended and volatile solids analyses	$ 436
2.	Field type dissolved oxygen probe and meter	108
3.	Incubator and associated apparatus for doing BOD analyses	2,976
4.	Kit and chemicals for ammonia analyses	573
5.	Kit for nitrite, nitrate and soluble phosphorus analyses	950
6.	Microscope having the capability of up to X400 magnification with an electrical light source	1,482
7.	Glassware associated with the above tests including 1 litre graduate cylinders for solids settling measurements	400
8.	pH meter and accessories	315
9.	Balance	800
		$8,040

Sample Preservation for Shipment

To preserve wastewater samples for nitrogen analyses, allyl thiourea (ATU) should be added either to the sampler container or to the sample bottle prior to shipment. A stock solution concentration of 1 g/l is used. One ml of this solution is added per litre of wastewater sample for preservation.